Asymmetric Dark Matter Stability from Continuous Flavor Symmetries

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Based on: FB and J. Zupan. arXiv:1408.3852

Outline

- ▷ Motivation
- ▷ ADM, DM stability, and flavor
- ▷ Asymmetric Dark Matter (ADM) mass
- ▷ ADM lifetime
- ▷ Mediator models
- ▷ Experimental constraints

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Motivation

- ▷ There is overwhelming evidence for the existence of DM yet the SM model lacks a candidate
- ▷ There is a coincidence $\Omega_\chi/\Omega_B = 5.4$; could there be a link?
- ▷ We expect New Physics (NP) at the TeV scale to address the hierarchy problem
- ▷ However, NP cannot have generic flavor structure
  - Large FCNCs if $\Lambda_{\rm NP} \sim$ TeV (NP flavor problem)
- ▷ Can flavor suppression lead to DM stability?

ADM, DM stability and flavor

There is a vast literature on the topic. Some examples include

- ADM

  Hooper, March-Russell & West [hep-ph/0410114], Kaplan, Luty & Zurek [aXv:0901.4117], Feldstein & Fitzpatrick [aXv:1003.5662], Dutta & Kumar [aXv:1012.1341], Cohen, Phalen, Pierce & Zurek [aXv:1005.1655], Falkowski, Ruderman & Volansky [aXv:1101.4936]

- MFV

  Kamenik & Zupan [aXv:1107.0623], Batell, Pradler & Spannowsky [aXv:1105.1781], Batell, Lin & Wang [aXv:1309.4462], SUSY MFV: Csaki, Grossman & Heidenreich [aXv:1111.1239], Monteux & Cornell [aXv:1404.5952]

- Lepton and quark flavored DM

  Agrawal, Blanchet, Chacko & Kilic [aXv:1109.3516], Kumar & Tulin [aXv:1303.0332], Agrawal, Batell, Hooper & Lin [aXv:1404.1373]

- Beyond MFV

  Agrawal, Blanke & Gemmler [aXv:1405.6709]

The roadmap

- $\triangleright$ Flavor & SM gauge singlet DM charged under $U(1)_{(B-L)}$

  $\Rightarrow$ DM is either a Dirac fermion or a complex scalar

- $\triangleright$ Assume that $B \neq 0$ and $L = 0$ to focus the discussion

- $\triangleright$ DM is a color singlet $\Rightarrow$ carries integer Baryon number

- $\triangleright$ Will not assume any discrete symmetry to stabilize DM

Goal

A cosmologically stable DM with $\Lambda_{\rm NP} \sim \mathcal{O}(\text{TeV})$

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ADM mass

Assumptions

- $B - L$ is a conserved quantum number
- Symmetric component efficiently annihilated

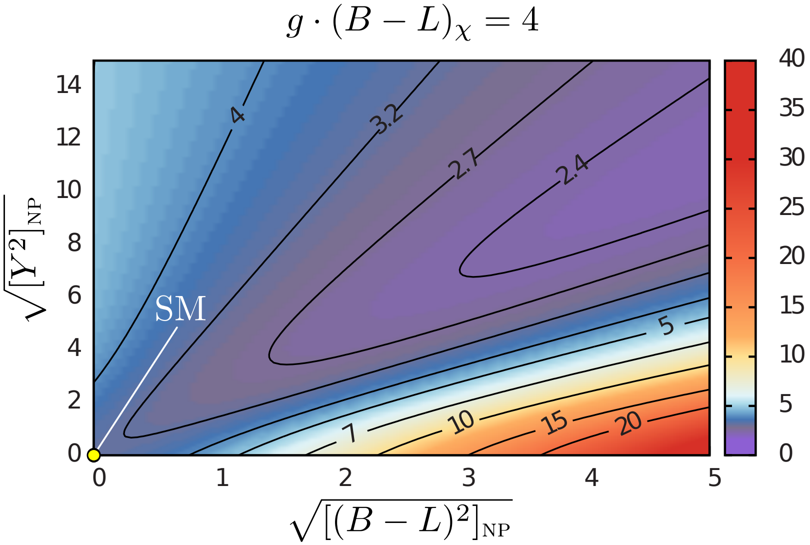
In this case, the ADM mass (with SM field content) is given by[1]

$$m_\chi = m_p \frac{\Omega_\chi}{\Omega_B}\left(\frac{B}{B-L}\right)\left(\frac{B-L}{\Delta\chi}\right) = (12.5 \pm 0.8\,\mathrm{GeV})\frac{1}{(B-L)_\chi^{\mathrm{sum}}}$$

where $\Delta\chi \equiv (n_\chi - \overline{n}_\chi)/s$ and $(B-L)_\chi^{\mathrm{sum}} \equiv \sum_i \hat{g}_\chi^i (B-L)_\chi^i$.

[1] Harvey & Turner, Phys.Rev. D42 (1990) 3344-3349; Feldstein & Fitzpatrick, arXiv:1003.5662.

ADM mass in the presence of New Physics (NP)



Asymmetric EFT operators

The lowest dimensional asymmetric operators are of the form

$$\mathcal{L} = \sum_i \frac{\mathcal{C}_i}{\Lambda^{(D_i-4)}} \, \chi \, \mathcal{O}_i^{\mathrm{SM}},$$

$$\text{with}^1 \; \mathcal{O}^{\mathrm{SM}} = [u^c]^{n_u} \; [d^c]^{n_d} \; [q^*]^{n_q} \,,$$

$$\text{and} \; \begin{cases} (n_d + n_u + n_q) \quad \mathrm{mod}\ 3 = 0 \\ n_d - n_u - n_q/2 = 0 \end{cases}$$

[1] The fields u^c and d^c are the $SU(2)_L$ singlet up and down type quark fields while q is the $SU(2)_L$ doublet quark field in two component spinor notation.

Freeze-out temperature of asymm. operators

- The NDA estimate for the freeze-out temperature is (FN flavor breaking)

$$T_f \sim \left(1.66 \times \sqrt{g_*}\,(16\pi^2)^3 \frac{8\pi}{C^2} \frac{\Lambda^{12}}{M_{\rm pl}}\right)^{1/11} \simeq 480\ \text{GeV} \left(\frac{\Lambda}{1.9\,\text{TeV}}\right)^{12/11}$$

- The EFT scale $\Lambda > 1.9$ TeV is bounded by indirect detection searches.
- Dominated by the $2 \to 5$ process.
- DM number is conserved below T_f.

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Metastability and flavor breaking

To calculate the DM lifetime we must

- Choose the flavor structure. We will consider two flavor breaking scenarios: Minimal Flavor Violation (MFV) and Froggatt-Nielsen (FN)
- Rotate to the mass eigenbasis. We will work in the down mass basis where

$$u^c \to u^c_{\text{MASS}}, \qquad d^c \to d^c_{\text{MASS}}, \qquad q = \begin{pmatrix} u \\ d \end{pmatrix} \to \begin{pmatrix} V_{\text{CKM}}\, u_{\text{MASS}} \\ d_{\text{MASS}} \end{pmatrix}.$$

  and the Yukawa matrices are

$$Y_D \to Y_D^{\text{diag}}, \quad Y_U \to V_{\text{CKM}} Y_U^{\text{diag}}$$

- Using Naive dimensional analysis (NDA), estimate DM total width

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Minimal Flavor Violation[1] (MFV)

- $\mathcal{L}_{\rm SM}$ enjoys an enhanced symmetry G_F in the limit $m_q \to 0$
- $G_F = SU(3)_Q \times SU(3)_U \times SU(3)_D$
- Symmetry is retained if Yukawa matrices are promoted to spurions that transform under G_F as

$$Y_U \sim (\mathbf{3}, \overline{\mathbf{3}}, \mathbf{1}), \qquad Y_D \sim (\mathbf{3}, \mathbf{1}, \overline{\mathbf{3}})$$

- The Yukawa interactions $u^c Y_U^\dagger q H$, $d^c Y_D^\dagger q H^c$ are then formally invariant under G_F

The SM Yukawas are the only source of flavor breaking.

[1] D'Ambrosio, Giudice, Isidori & Strumia [hep-ph/0207036]

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Example: $B = 1$ operators with MFV

$$\mathcal{O}_1^{(B=1)} = (\chi\, u^c)(d^c d^c), \quad \mathcal{O}_2^{(B=1)} = (\chi\, q^*_\rho)(d^c\, q^*_\sigma)\epsilon^{\rho\sigma}$$

$$\begin{aligned}
\mathcal{O}_1^{(B=1)} &= \left(\chi\, u^c_\alpha Y_U^\dagger Y_D\right)_K \left(d^c_{N\beta} d^c_{M\gamma}\right)\epsilon^{KNM}\epsilon^{\alpha\beta\gamma} \\
&\to \left(\chi\, u^c_{\mathrm{MASS}} Y_U^{\mathrm{diag}\dagger} V^\dagger_{\mathrm{CKM}} Y_D^{\mathrm{diag}}\right)_{K\alpha}\left([d^c_{\mathrm{MASS}}]_{N\beta}\,[d^c_{\mathrm{MASS}}]_{M\gamma}\right)\epsilon^{KNM}\epsilon^{\alpha\beta\gamma}, \\
\mathcal{O}_2^{(B=1)} &= (\chi\, q^*_{K\alpha i})([d^c_\beta Y_D^\dagger]_N q^*_{M\gamma j})\epsilon^{ij}\epsilon^{KNM}\epsilon^{\alpha\beta\gamma} \\
&\to \left(\chi\, u^*_{\mathrm{MASS}} V^\dagger_{\mathrm{CKM}}\right)_{K\alpha}\left([d^c_{\mathrm{MASS}} Y_D^{\mathrm{diag}\dagger}]_{N\beta}[d^*_{\mathrm{MASS}}]_{M\gamma}\right)\epsilon^{KNM}\epsilon^{\alpha\beta\gamma},
\end{aligned}$$

$$\begin{aligned}
\Gamma_\chi^{(1)} &\sim \frac{(y_t y_b)^2}{8\pi}\left(\frac{m_\chi}{\Lambda}\right)^4\left(\frac{1}{16\pi^2}\frac{m_t\Lambda_{\mathrm{QCD}}}{m_W^2}\right)^2\frac{m_\chi}{16\pi^2} \\
&= 6.6\cdot 10^{-51}\mathrm{GeV}\left(\frac{y_b}{0.024}\right)^2\left(\frac{5.3\cdot 10^6\mathrm{TeV}}{\Lambda}\right)^4,
\end{aligned}$$

$$\Gamma_\chi^{(2)} \sim \frac{|y_b V_{ub}|^2}{8\pi}\left(\frac{m_\chi}{\Lambda}\right)^4\frac{m_\chi}{16\pi^2} = 6.6\cdot 10^{-51}\mathrm{GeV}\left(\frac{y_b}{0.024}\right)^2\left(\frac{4.8\cdot 10^7\mathrm{TeV}}{\Lambda}\right)^4$$

Example: $B = 1$ operators with MFV

$$\mathcal{O}_1^{(B=1)} = (\chi\, u^c)(d^c d^c), \quad \mathcal{O}_2^{(B=1)} = (\chi\, q^*_\rho)(d^c\, q^*_\sigma)\epsilon^{\rho\sigma}$$

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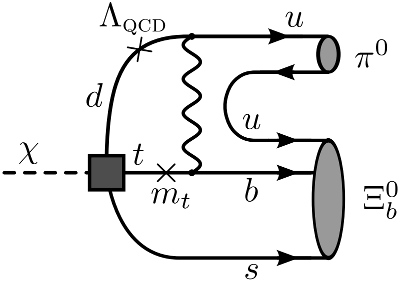

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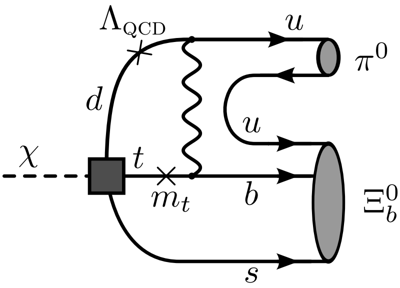

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DM leading decays and EFT scale

ADM model			MFV			FN		
B	Dim.	m_χ [GeV]	decay	τ [s]	Λ [TeV]	decay	τ [s]	Λ [TeV]
1	6	6.2	$\chi \to bus$	10^{26}	4.0×10^6	$\chi \to bus$	10^{26}	8.1×10^8
2	10	3.1	$\chi \to udsuds$	10^{26}	0.63	$\chi \to udsuds$	10^{26}	2.5
3	15	2.1	forbidden	∞	–	forbidden	∞	–

Table: Leading decay modes for the $B = \{1, 2, 3\}$ operators with MFV and FN flavor breaking. The scale Λ_* is calculated such that the lifetime of the DM $\tau \sim 10^{26}$ [s]. The decay of ADM with $B = 3$ is kinematically forbidden.

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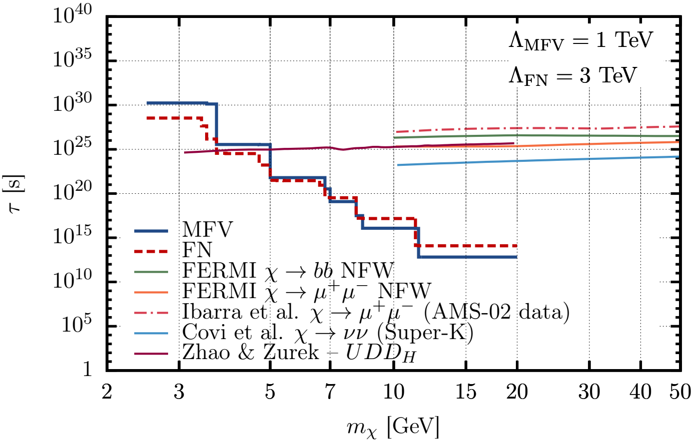
ADM lifetime



Ackermann et al. [aXv:1205.6474]; Ibarra, Lamperstorfer, & Silk [aXv:1309.2570]; Aguilar et al. [Phys.Rev.Lett. 110, 141102 (2013)]; Covi, Grefe, Ibarra, & Tran [aXv:0912.3521]; Desai et al. [aXv:hep-ex/0404025]; Zhao & Zurek [aXv:1401.7664]

Mediator models

MFV model with scalar mediators

$$\begin{aligned}\mathcal{L}_{\text{INT}} \supset\, & \kappa_1[\phi_L]^{AB}_{\gamma}\left(q^*_{A,\alpha i}q^*_{B,\beta j}\right)\epsilon^{ij}\epsilon^{\alpha\beta\gamma} + \kappa_2[\varphi_L]^{\alpha\beta}_{A}\left(q^*_{B,\alpha i}q^*_{C,\beta j}\right)\epsilon^{ij}\epsilon^{ABC} \\ & + \kappa_3[Y_D]^{A}_{X}[\phi_R]_{A,\alpha}\left(d^c_{Y,\beta}\, d^c_{Z,\gamma}\right)\epsilon^{\alpha\beta\gamma}\epsilon^{XYZ} + \kappa_4\chi^\dagger[\phi_L]^{AB}_{\alpha}[\varphi_L]^{\alpha\beta}_{A}[\phi_R]_{B,\beta} \\ & + h.c.\end{aligned}$$

The gauge and global charge assignment for the three scalar mediators, ϕ_L, φ_L and ϕ_R, in the first UV completion toy model for which we also assume the MFV flavor breaking pattern

Field	$SU(3)_C$	$SU(2)_L$	$U(1)_Y$	G_F	$U(1)_{B-L}$
ϕ_L	$\bar{\mathbf{3}}$	$\mathbf{1}$	$1/3$	$(\mathbf{6},\mathbf{1},\mathbf{1})$	$2/3$
φ_L	$\mathbf{6}$	$\mathbf{1}$	$1/3$	$(\bar{\mathbf{3}},\mathbf{1},\mathbf{1})$	$2/3$
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MFV model with scalar mediators

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$$+\kappa_3[Y_D]^A_X[\phi_R]_{A,\alpha}\left(d^c_{Y,\beta}\,d^c_{Z,\gamma}\right)\epsilon^{\alpha\beta\gamma}\epsilon^{XYZ} + \kappa_4\chi^\dagger[\phi_L]^{AB}_{\alpha}[\varphi_L]^{\alpha\beta}_{A}[\phi_R]_{B,\beta}$$
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ϕ_R	$\bar{\mathbf{3}}$	$\mathbf{1}$	$-2/3$	$(\bar{\mathbf{3}},\mathbf{1},\mathbf{1})$	$2/3$

MFV model with scalar mediators

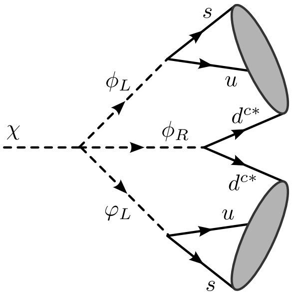
$$\mathcal{L}_{\text{INT}} \supset \kappa_1 [\phi_L]^{AB}_{\gamma} \left(q^*_{A,\alpha i} q^*_{B,\beta j} \right) \epsilon^{ij} \epsilon^{\alpha\beta\gamma} + \kappa_2 [\varphi_L]^{\alpha\beta}_{A} \left(q^*_{B,\alpha i} q^*_{C,\beta j} \right) \epsilon^{ij} \epsilon^{ABC}$$
$$+ \kappa_3 [Y_D]^{A}_{X} [\phi_R]_{A,\alpha} \left(d^c_{Y,\beta}\, d^c_{Z,\gamma} \right) \epsilon^{\alpha\beta\gamma} \epsilon^{XYZ} + \kappa_4 \chi^\dagger [\phi_L]^{AB}_{\alpha} [\varphi_L]^{\alpha\beta}_{A} [\phi_R]_{B,\beta}$$
$$+ h.c.$$

The gauge and global charge assignment for the three scalar mediators, ϕ_L, φ_L and ϕ_R, in the first UV completion toy model for which we also assume the MFV flavor breaking pattern

Field	$SU(3)_C$	$SU(2)_L$	$U(1)_Y$	G_F	$U(1)_{B-L}$
ϕ_L	$\overline{\mathbf{3}}$	$\mathbf{1}$	$1/3$	$(\mathbf{6}, \mathbf{1}, \mathbf{1})$	$2/3$
φ_L	$\mathbf{6}$	$\mathbf{1}$	$1/3$	$(\overline{\mathbf{3}}, \mathbf{1}, \mathbf{1})$	$2/3$
ϕ_R	$\overline{\mathbf{3}}$	$\mathbf{1}$	$-2/3$	$(\overline{\mathbf{3}}, \mathbf{1}, \mathbf{1})$	$2/3$

MFV model with scalar mediators

$$\mathcal{L}_{\rm INT} \supset \kappa_1[\phi_L]^{AB}_{\gamma}\left(q^*_{A,\alpha i}q^*_{B,\beta j}\right)\epsilon^{ij}\epsilon^{\alpha\beta\gamma} + \kappa_2[\varphi_L]^{\alpha\beta}_{A}\left(q^*_{B,\alpha i}q^*_{C,\beta j}\right)\epsilon^{ij}\epsilon^{ABC}$$
$$+ \kappa_3[Y_D]^{A}_{X}[\phi_R]_{A,\alpha}\left(d^c_{Y,\beta}\, d^c_{Z,\gamma}\right)\epsilon^{\alpha\beta\gamma}\epsilon^{XYZ} + \kappa_4\chi^\dagger[\phi_L]^{AB}_{\alpha}[\varphi_L]^{\alpha\beta}_{A}[\phi_R]_{B,\beta}$$
$$+ h.c.$$



FN model with scalar and fermionic mediators

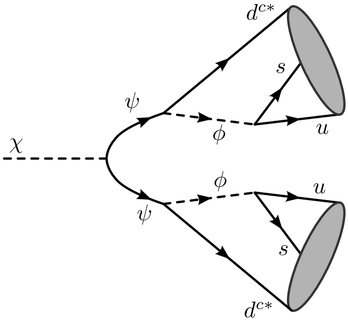
$$\mathcal{L}_{\rm INT} \supset g_{q,AB}\phi_\gamma \left(q^{*j}_{A,\alpha i} q^{*k}_{B,\beta j} \right) \epsilon^{ij}\epsilon^{\alpha\beta\gamma} + g_{d,A}\phi^{*\alpha} \left(d^c_{A,\alpha}\,\psi \right) + g_\chi\,\chi(\psi^c\,\psi^c) + h.c.$$

Gauge and $B-L$ charges of the mediators ϕ and ψ in the second UV model. We also assume FN flavor breaking pattern

Field	$SU(3)_C$	$SU(2)_L$	$U(1)_Y$	$U(1)_{B-L}$
ϕ	$\bar{\mathbf{3}}$	$\mathbf{1}$	$1/3$	$2/3$
ψ	$\mathbf{1}$	$\mathbf{1}$	0	1

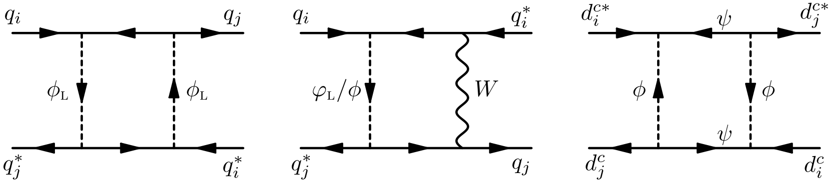
FN model with scalar and fermionic mediators

$$\mathcal{L}_{\text{INT}} \supset g_{q,AB}\phi_\gamma \left(q^{*j}_{A,\alpha i} q^{*k}_{B,\beta j}\right)\epsilon^{ij}\epsilon^{\alpha\beta\gamma} + g_{d,A}\phi^{*\alpha}\left(d^c_{A,\alpha}\,\psi\right) + g_\chi\,\chi(\psi^c\,\psi^c) + h.c.$$



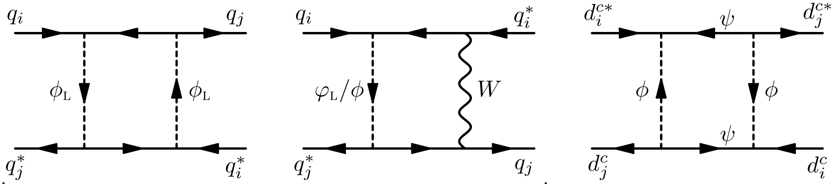
Flavor constraints

Mediators contribute to $\Delta_F = 2$ processes at the one loop level via



Flavor constraints

Mediators contribute to $\Delta_F = 2$ processes at the one loop level via



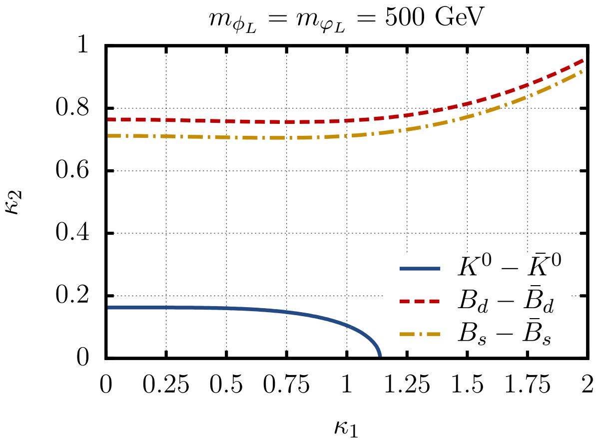
As in the SM, there is a GIM cancellation in these diagrams and the contribution is additionally suppressed by the internal quark Yukawa.

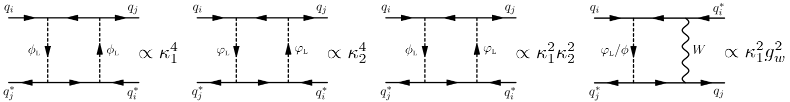
Flavor constraints

	MFV		FN	
	$\kappa_{1,2} <$	$m_{\phi_L,\varphi_L} >$	$g_{q,d} <$	$m_\phi >$
$K^0 - \bar{K}^0$	0.33	2.9 TeV	0.63	570 GeV
$B_d - \bar{B}_d$	1.3	710 GeV	0.54	1 TeV
$B_s - \bar{B}_s$	1.3	780 GeV	0.59	840 GeV
$D^0 - \bar{D}^0$	30	34 GeV	4.3	56 GeV

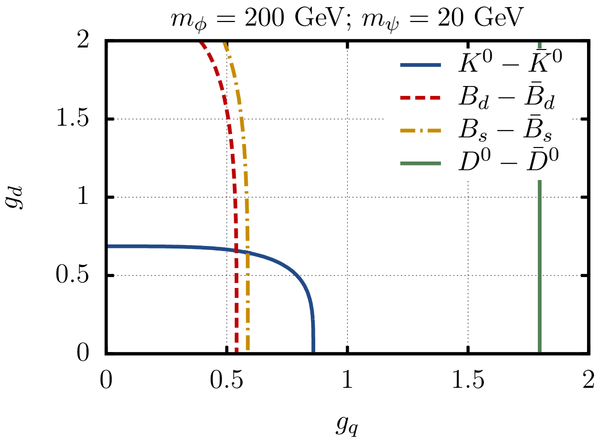
Table: The 95 % C.L. bounds on the MFV and FN mediator models from meson mixing. Taking $m_{\phi_L} = m_{\varphi_L} = m_\phi = 1$TeV and $\kappa_1 = \kappa_2$ gives the upper bounds on the couplings in the 2nd column and 4th column for $g_q = g_d$. Taking $\kappa_{1,2} = g_{q,d} = 1$ gives lower bounds on the mediator masses in the 3rd and 5th columns. The mass of the fermion in the FN model is fixed to $m_\psi = 20$ GeV.

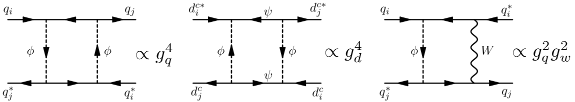
Flavor constraints – MFV mediator model



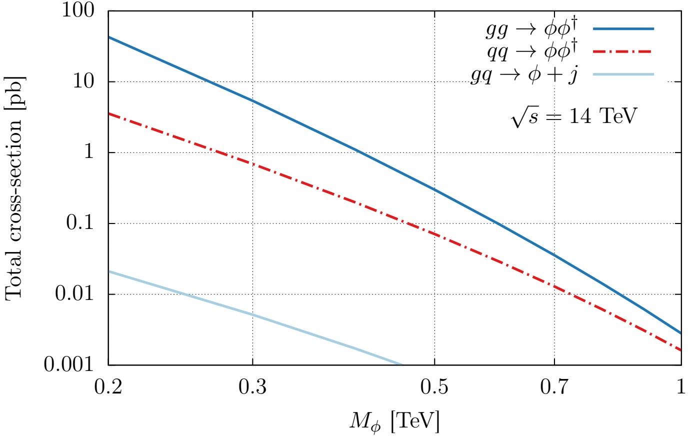


Flavor constraints – FN mediator model

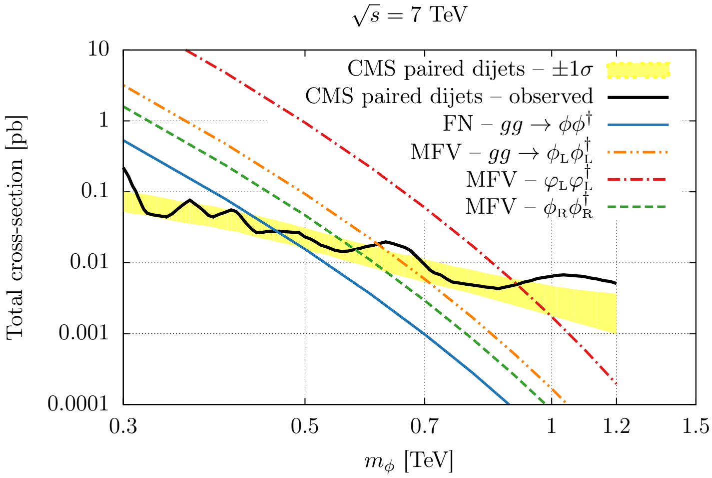




Collider signatures: single and pair production

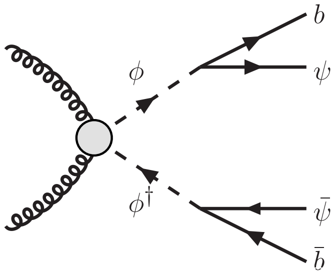


Collider signatures: paired dijets constraints



Search for New Physics in the Paired Dijet Mass Spectrum – CMS. [arXiv:1302.0531]

Collider signatures: $2b$ jets + MET



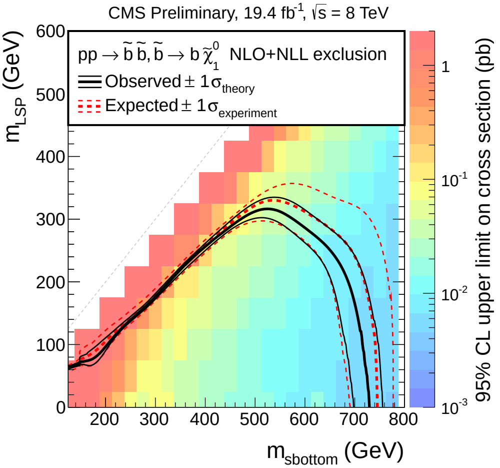
- The NDA decay length of ψ is given by

$$c\tau(\psi \to bbc) \sim \left(g_q^2 g_d^2 \lambda^8 \frac{1}{8\pi} \frac{1}{16\pi^2} \frac{m_\psi^5}{m_\phi^4} \right)^{-1}$$

$$\sim 30\text{m} \left(\frac{20\,\text{GeV}}{m_\psi} \right)^5 \left(\frac{m_\phi}{750\,\text{GeV}} \right)^4 \left(\frac{0.03}{g_q g_d} \right)^2$$

Collider signatures: 2b jets + MET

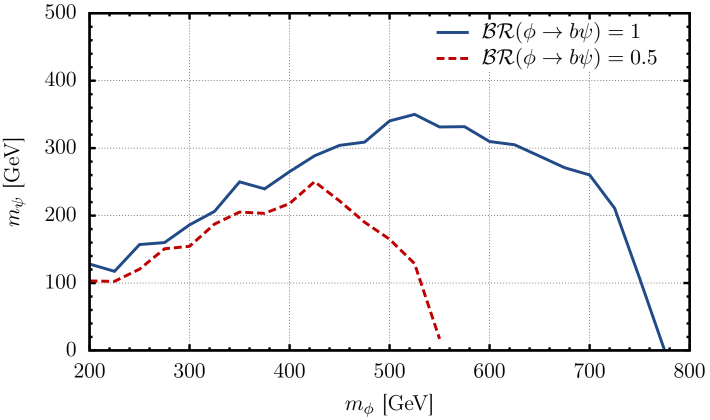
Constraints from sbottom pair production



Search for direct production of a pair of bottom squarks – CMS. [PAS-SUS-13-018]

Collider signatures: 2b jets + MET

Constraints from sbottom pair production



Search for direct production of a pair of bottom squarks – CMS. [PAS-SUS-13-018]

Summary & conclusions

- ▷ Showed that flavor symmetries can allow us to have a cosmologically stable ADM even if the DM is not charged under the flavor group
- ▷ The mediators between the visible and dark sectors can be at the TeV scale without giving rise to dangerous FCNCs
- ▷ The mediator models can have interesting signatures at the LHC

Backup

$U(1)$ Froggatt-Nielsen[1] (FN) model

- Spontaneously broken horizontal $U(1)$ symmetry
- Quarks carry horizontal charges under this $U(1)$
- E.g., horizontal charge assignment that gives phenomenologically satisfactory quark masses and CKM matrix elements[2]

$$H(q, d^c, u^c) \Rightarrow \begin{array}{cc} & \begin{array}{ccc} 1 & 2 & 3 \end{array} \\ \begin{array}{c} q \\ d^c \\ u^c \end{array} & \begin{pmatrix} 3 & 2 & 0 \\ 3 & 2 & 2 \\ 3 & 1 & 0 \end{pmatrix} \end{array}$$

- Wilson coefficients $\mathcal{C} = \lambda^{|\sum_i H_i|}$, where $\lambda = 0.2$

[1] Froggatt & Nielsen [Nucl.Phys. B147 (1979) 277]
[2] Leurer, Nir & Seiberg [hep-ph/9310320], [hep-ph/9212278]